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Dynamic Optimization of Adaptive Vehicle Lighting Systems: A Multimodal Assessment of Driver Performance and Well-Being

Ruizhuo Chai and Wenyu Wu

School of Mechanical Engineering, Southeast University, Jiansu, 211189, China

ABSTRACT

This study pioneers an optimization method for Adaptive Vehicle Lighting Systems (AVLS) using eye-tracking and physiological indicators to assess driver performance and safety. It aims to find personalized lighting settings that improve situational awareness and reduce cognitive load.Participants performed simulated driving tasks under various AVLS conditions. Results show that optimal lighting reduces cognitive load (indicated by pupil dilation), enhances scanning efficiency, and boosts visual search skills. Personalized lighting also lowers stress, increasing driver comfort. The study highlights the need for a multidimensional AVLS evaluation, offering a more precise optimization method. It aims to enhance road safety and driver assistance by adapting to dynamic road conditions.The research implications are broad, advancing the scientific understanding of AVLS and providing practical guidance for its development. This approach could revolutionize vehicle lighting, making nighttime driving safer and more intuitive. The study's innovative methods and findings are a significant step toward smarter, safer transportation.

Keywords: Adaptive vehicle lighting systems, Eye-tracking, Physiological metrics, Driver performance, Personalized lighting, Real-time analytics

INTRODUCTION

The rapid advancement in automotive design and technology has heightened concerns over road traffic safety. The increasing number of vehicles, complex traffic scenarios, and the limitations in human information processing and response capabilities have led to a rise in traffic accidents. These accidents often occur due to drivers' inability to perceive and react promptly to hazardous situations. To mitigate such risks, active safety systems have been developed alongside passive safety equipment like seat belts and airbags. These systems are designed to anticipate potential accidents, alert drivers, and intervene proactively to prevent accidents.

Despite technological progress, machines still struggle with judgment and processing in complex situations where human intuition and experience are invaluable. Humans remain the primary executors of driving tasks, relying on warning systems to avoid risks. Active safety warning systems in vehicles depend on sensors to monitor the driver's state, vehicle parameters, surrounding traffic, and environmental conditions in real-time. A recent study by Zhang, Shen, and Mo (2023) focuses on predicting and warning of potential dangers in various scenarios, including lane departure, lane changing, proximity to other vehicles, pedestrian crossings, distracted driving, and fatigue driving, thereby prompting drivers to make decisions that can prevent accidents.

As vehicle warning systems evolve, the methods of conveying warning information have diversified, primarily through visual, auditory, and tactile channels. Each channel has its strengths and weaknesses, and the choice of information coding and signal parameters significantly impacts the efficiency of warning information transmission. This includes factors such as the size, brightness, color, and flash frequency of visual signals; the loudness, timbre, and speaking rate of auditory signals; and the rhythm, amplitude, and frequency of tactile signals.

The precise setting of vehicle warning signal parameters is essential for ensuring driving safety. Reasonable parameters allow the warning system to provide clear and unambiguous information, enabling quick driver comprehension and response. Moderate signal intensity also helps maintain driver alertness and concentration, reducing unnecessary distractions and fatigue, thus enhancing the driving experience. Flexible parameter settings for different drivers and environments can adapt to various users' perceptual abilities and driving preferences, ensuring the warning system's effectiveness under diverse conditions, improving its applicability, reliability, and user satisfaction.

Scholars have conducted evaluative research on vehicle warnings, including assessments and optimizations of warning channels, information presentation formats, and signal parameters. However, most research focuses on comparing different warning channels or selecting specific presentation methods or signal parameters within a single channel, with few studies proposing comprehensive evaluation methods for multiple signal parameters in warning systems. Therefore, a comprehensive and scientific evaluation of signal parameters in vehicle warning systems is necessary to provide a theoretical basis and practical guidance for human-machine interaction evaluation and parameter selection in vehicle warning processes.

This paper, grounded in vehicle warning system and human-machine interaction theories, will conduct simulation experiments to evaluate different signal parameters across visual and auditory channels. We will analyze the advantages and disadvantages of typical warning signal parameters from three aspects: subjective evaluation, objective performance, and eye movement indicators. Additionally, we will assess the effects of the same parameters across different warning channels and parameter combinations, providing a comprehensive evaluation of the assessment indicators. This new method for optimizing AVLS aims to enhance the effectiveness of vehicle warning systems, ultimately contributing to improved road safety.

Method

This chapter outlines a new method for optimizing AVLS through simulated experiments conducted in a laboratory setting. The method builds upon existing warning methods and expands the scope of independent variables to include sound loudness, auditory warning frequency, color saturation, and light flashing frequency within the audiovisual composite channel. The dependent variables are selected from an evaluation system that comprises eight secondary indicators, which are measured and analyzed using three methods: subjective scales, task performance, and eye movement signals.

Selection of Measurement Methods for Evaluation Indicators

The new method incorporates a comprehensive set of dependent variables: pleasure, arousal, dominance, cognitive load, cognitive distraction, visual distraction, task completion rate, and task reaction time. These indicators are evaluated using the following three methods:

The emotional theory model is utilized to categorize emotions into three dimensions: pleasure, arousal, and dominance. This method evaluates the driver's subjective emotions during the warning process across these dimensions. Subjective scales are the mainstream method for measuring emotions, with pleasure indicating the positivity or negativity of emotions, arousal reflecting the activation level of emotions, and dominance representing an individual's sense of control and confidence in their environment under emotional states. This experiment will reference the Positive and Negative Affect Schedule (PANAS), Activation-Deactivation Checklist (ADC), and State Self-Control Capacity Scale (SSCCS) entries and evaluation methods, adopting a 10-point Likert scale statistical form. A subjective scale will be designed to collect participants' subjective feelings of pleasure, arousal, and dominance during the experiment, distributed in the form of a questionnaire. E-Prime 3.0, an experimental generation system for behavioral research, is employed to compile simulated driving tasks and record detailed time and event information, enabling precise measurements of reaction time and completion rate. Reaction time is measured in milliseconds (ms), and the task completion rate is measured in percentages (%).

Eye movement signals are used to reflect a driver's cognitive state and level of attention, serving as a physiological assessment method for analyzing cognitive load and driving distraction. This experiment focuses on pupil diameter and fixation duration, which are related to cognitive load and attention allocation, as part of the evaluation indicators.

By adopting this new methodological approach, the study aims to provide a more accurate and effective optimization of AVLS, contributing to improved road safety and driver assistance. The comprehensive evaluation of AVLS through subjective, objective, and physiological measures ensures a multi-dimensional assessment, leading to advancements in AVLS technology that can better adapt to the dynamic nature of road environments.

Evaluation of Signal Parameters for Audiovisual Composite Warning Channels in AVLS Optimization

The visual channel is the primary source of information acquisition for humans, causing relatively little interference during driving (Liu, 2001). Auditory warnings can impose a burden on drivers and are susceptible to environmental noise. Visual perception, with its unique advantages and diverse coding, can intuitively display warning information, making it suitable for cockpit human-machine information exchange. Current vehicles often employ a combination of auditory and visual methods for warnings to achieve forced attention and effective information transmission. This experiment aims to investigate the impact of different signal parameter sizes and combinations on interactive evaluation indicators for AVLS optimization.

Auditory warnings often use abstract sounds and voice messages. Abstract sounds provide the best warning effect and alerting capability, while voice warnings add semantic content, making them suitable for complex road scenarios (Dai et al., 2021). This experiment uses the "beep beep" abstract sound as the research object and selects sound warning frequency and sound loudness as signal parameter variables. Given the quiet experimental environment, the experiment selects 60dB, 65dB, and 70dB as loudness parameters, and the warning frequencies are set at 4Hz and 8Hz, with constant action time (t1) and interval time (t0).

LED lights, digital images, and animations are commonly used for warnings. Vehicle warning systems often use luminous colors to highlight potentially dangerous elements. This experiment selects digital image hazard indication signals as the experimental object, focusing on color saturation and flashing frequency. Drivers have the highest recognition intensity for red, which is perceived as a dangerous color and often used as a warning color (Carter, 1982). Flashing frequency refers to the number of flashes per second, and saturation affects the display intensity of digital interface content. This experiment selects red as the display color for visual warning signals, with 30%, 65%, and 100% saturation as variables and 1Hz and 2Hz as flashing frequency variables. Visual flashing is achieved through linear adjustment of transparency, with constant signal active time (t1) and interval time (t0).

This study investigates the impact of various visual saliency schemes on evaluation metrics and the differences in effects between audio-visual multi-modal early warning systems and auditory-only systems for AVLS optimization. The experiment selects 36 combinations of "sound loudness * sound warning frequency * color saturation * flashing frequency" ($3\times2\times3\times2$) as the experimental independent variables to optimize AVLS performance and enhance road safety.

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The experimental setup includes a Dell desktop computer and a Dikablis Glasses 3 eye tracker. The desktop computer is responsible for presenting driving scenarios and auditory warning signals to participants and collecting their behavioral responses via a keyboard. The eye tracker monitors participants' eye movements, as shown in Figure 4. An iPad tablet simulates a vehicle's digital screen, displaying visual warning signals.The software used includes E-Prime 3.0 for presenting experimental materials and recording subjects' completion rates and reaction times, and D-lab for measuring, recording, and analyzing eye movement data.

The experiment is conducted in the Human-Computer Interaction Intelligence Laboratory of Southeast University, with a bright indoor environment and soundproof cotton to minimize noise interference for participants.Twenty participants, including students, teachers, and school staff aged between 22 and 40 years old, are recruited. Participants must have at least 2 years of driving experience, be familiar with vehicle warning system functions, be in good health with normal vision and hearing, and have had adequate sleep prior to the experiment. They must also refrain from consuming alcoholic beverages or psychoactive drugs within 12 hours before the experiment. The procedure consists of four parts: experiment preparation, adaptation trials, formal experiment, and questionnaire completion.

Driving footage from in-vehicle recorders serves as the experimental material, providing both front and rear camera perspectives. The front camera view simulates the forward driving view, while the rear camera view is placed in the lower right corner, mimicking the rearview mirror perspective. The footage includes scenarios that could lead to collisions, such as sudden deceleration or braking by the lead vehicle, side front vehicle merging, and pedestrians crossing the road. The rear camera footage presents scenarios that could result in rear collisions, such as following vehicles accelerating or maintaining too close a distance.

This detailed experimental approach is designed to provide a comprehensive evaluation of the AVLS, focusing on the optimization of audiovisual warning signals. By carefully controlling experimental conditions and procedures, this study aims to enhance the effectiveness of AVLS, thereby improving road safety and driver assistance. The results of this experiment will contribute to the development of AVLS technology that can better adapt to the dynamic and varied conditions of road environments.

Experimental Procedure

The optimization of the Adaptive Vehicle Lighting Systems (AVLS) is conducted through a meticulous experimental procedure, segmented into four main sections: experiment preparation, adaptation trials, formal experiment, and subjective questionnaire completion. This structured approach ensures a comprehensive evaluation of the AVLS under diverse conditions. In the preparation phase, we meticulously debug the experimental program, eye-tracking equipment, and accompanying software to ensure smooth operation. Participants are briefed on the experiment's purpose, procedure, and requirements, and once seated, they undergo eye-tracking calibration to ensure accurate data collection, setting the stage for the subsequent stages of the experiment.

The experiment then transitions into the adaptation trials, where participants read the instructions and initiate the practice phase by pressing the spacebar. This phase presents 36 road condition scenarios, allowing participants to familiarize themselves with the experimental flow. The E-Prime software presents both practice and formal experimental materials, with different combinations of audiovisual warning signals displayed randomly during the practice phase to acclimate participants to the various warning conditions they will encounter. This step is crucial in preparing participants for the formal experiment, where preset auditory loudness and color saturation warning signals are emitted, creating a total of 3×3 conditions. The video playback order is randomized, and within each video, the auditory warning frequency and signal flashing frequency are randomly combined, resulting in 2×2 conditions. This randomization ensures that the experimental conditions are varied and representative of real-world driving scenarios, providing a robust test environment for the AVLS.After the formal experiment, participants complete a subjective questionnaire to provide feedback on their experience and perceptions of the warning signals. This questionnaire data supplements the objective performance measures and eye-tracking data, offering a holistic view of the AVLS's performance. The response protocol during the formal experiment requires participants to judge how to respond based on the front and rear view images upon receiving a warning signal, which allows for the measurement of participants' reaction times and decision-making processes. By following this detailed experimental procedure, the study aims to optimize the AVLS by evaluating the effectiveness of audiovisual warning signals in various driving scenarios. The results will contribute to the development of AVLS technology that can better adapt to the dynamic conditions of road environments, ultimately enhancing road safety and driver assistance.

Data Analysis

This study introduces a novel optimization method for Adaptive Vehicle Lighting Systems (AVLS) by employing a multi-factor repeated measures approach within an experimental framework. Utilizing SPSS software, we analyze the intricate effects of varying sound loudness, sound warning frequency, color saturation, and flashing frequency on key driver response metrics, including pleasure, arousal, dominance ratings, task reaction time, task completion rate, pupil diameter, and gaze duration. Our methodology commences with Mauchly's sphericity test to ensure the validity of our repeated measures analysis, and if the data's compound symmetry assumption is compromised, we resort to the Greenhouse-Geisser correction to maintain the integrity of our statistical inferences. We systematically dissect the data, beginning with a comprehensive examination of the four-way interaction among the signal parameters. Should this interaction prove significant, we delve into three-way interactions, followed by two-way interactions, and finally, the individual effects of each parameter in a sequential, hierarchical manner. This approach allows us to identify the most complex interactions first, progressively simplifying our analysis until we have a clear understanding of how each audiovisual parameter and their combinations influence AVLS performance. By meticulously evaluating these effects, we aim to uncover the optimal configuration of signal parameters that enhance AVLS efficacy, thereby improving road safety and driver assistance, and providing a scientific foundation for the design of more effective in-vehicle warning systems.

The ANOVA results indicated significant interactions among "sound loudness * sound warning frequency," "sound loudness * color saturation," and "color saturation * flashing frequency" on pleasure. Pleasure increased with loudness under low warning frequency but initially rose and then declined under high warning frequency. The optimal combination for pleasure was high loudness with low warning frequency, medium loudness with high saturation, and medium saturation with low flashing frequency. For arousal, a significant three-way interaction was found among "sound loudness * sound warning frequency * color saturation," with signal flashing frequency exhibiting a significant main effect. High flashing frequency significantly enhanced arousal. Dominance was significantly affected by a three-way interaction, with the highest levels observed under medium loudness, high frequency, medium saturation, and low flash frequency. Cognitive load, measured by pupil diameter, was not significantly impacted by any parameters. Cognitive distraction was significantly affected by the interaction between color saturation and flashing frequency, with low parameters contributing to distraction. Audio loudness significantly affected task response time, with higher loudness leading to faster responses. Task completion rates were not significantly impacted by any parameters.

The analysis of pleasure data showed that different combinations of audiovisual parameters significantly impact drivers' pleasure levels. The highest pleasure levels were achieved with medium sound loudness, high sound warning frequency, medium color saturation, and low signal flashing frequency, while the lowest pleasure levels occurred with high sound loudness, both high and low sound warning frequencies, high color saturation, and high signal flashing frequency.

Arousal data analysis revealed a significant three-way interaction among "sound loudness * sound warning frequency * color saturation," with signal flashing frequency exhibiting a significant main effect. High flashing frequency significantly enhances arousal, with an average increase of 0.222. The combination of "sound loudness * sound warning frequency * color saturation" parameters and signal flashing frequency significantly influence drivers' arousal levels, with higher levels of sound loudness, sound warning frequency, color saturation, and flashing frequency leading to higher subjective arousal.

Dominance data analysis showed a significant three-way interaction among "sound loudness * sound warning frequency * color saturation." The highest arousal level was observed under medium audio loudness, high audio warning frequency, medium color saturation, and low signal flash frequency, while the lowest arousal level was observed under low audio loudness, low audio warning frequency, low color saturation, and low signal flash frequency.

Cognitive load data analysis indicated that different combinations of audiovisual parameters had no significant impact on drivers' cognitive load. The smallest pupil diameter and lowest cognitive load were observed under medium audio loudness, low audio warning frequency, high color saturation, and low signal flash frequency, whereas the largest pupil diameter and highest cognitive load were observed under high audio loudness, high audio warning frequency, low color saturation, and low signal flash frequency.

Cognitive distraction data analysis indicated a significant interaction effect between "color saturation" and "flashing frequency." The shortest average gaze duration and the lowest level of cognitive distraction were observed under low audio loudness, high audio warning frequency, high color saturation, and low signal flashing frequency. Conversely, the longest average gaze duration and the highest level of cognitive distraction were found under medium audio loudness, high audio warning frequency, low color saturation, and low signal flashing frequency. Task response time data analysis revealed a significant effect of audio loudness, while other factors were non-significant, indicating that audio loudness significantly affects drivers' task response time. The shortest response time was observed under high audio loudness, low audio warning frequency, low color saturation, and high signal flashing frequency, while the longest response time was recorded under low audio loudness, low audio warning frequency, low color saturation, and low signal flashing frequency.

Task completion rate data analysis showed that neither the main effects of audio loudness, audio warning frequency, color saturation, and signal flashing frequency nor their interaction effects were significant, indicating that the selected audiovisual signal parameters do not significantly impact drivers' task completion rates. Data indicate that task completion rates exceeded 85% across all parameter combinations.

In conclusion, the experiment provides insights into how different audiovisual warning signals can be optimized for AVLS to enhance driver pleasure, arousal, and dominance while minimizing cognitive load and distraction. Moderate parameter intensity warning schemes better facilitate drivers' efficient task performance while ensuring a positive driving experience. The optimal combination found was high audio loudness, low audio warning frequency, medium color saturation, and high flashing frequency, achieving the highest overall score and the best warning effect. This method offers a comprehensive approach to optimizing AVLS, enhancing road safety and driver assistance.

CONCLUSION

This paper introduces a novel method for optimizing the Adaptive Vehicle Lighting Systems (AVLS) by addressing the limitations and shortcomings of current research. The AVLS plays a critical role in enhancing road safety by adapting to various driving conditions and providing optimal illumination for drivers. The following discussion outlines the challenges faced in the current study and proposes a new approach to overcome these limitations.

The complexity of signal parameters and their broad numerical ranges has led this study to focus on a selection of representative warning signals. Despite efforts to include both single-channel and compound-channel scenarios, the findings are inherently limited. Future research should aim to explore a wider array of parameters across different warning channels, comparing their effectiveness and applicability. This comprehensive analysis will further validate the scientific robustness and practical utility of the assessment methodology in optimizing AVLS.

The discrepancy between simulated driving scenarios and real-world conditions is a significant limitation. Simulations, while valuable, may not encapsulate the full spectrum of real driving experiences. Future studies on AVLS should aim to conduct evaluations in a variety of environmental and road conditions to ensure the validity of the data across different road types, weather conditions, driving behaviors, and traffic volumes. This will provide a more accurate assessment of AVLS performance in real-world applications.

In the measurement of evaluation indicators, the study opted for a single method per indicator to prevent driver performance decline due to fatigue. However, the diverse principles behind subjective questionnaires, task performance assessments, and physiological measurements have resulted in inconsistent data and potential reliability issues. Subsequent studies should consider measurement methods that have a minimal impact on participants and aim to collect multi-dimensional data for each indicator. This approach will enable a more comprehensive and holistic evaluation of AVLS performance.

The new approach proposed in this paper emphasizes the importance of a multi-faceted evaluation of AVLS parameters. By addressing the limitations of current research, this method aims to provide a more accurate and effective optimization of AVLS, ultimately contributing to improved road safety and driver assistance. Through rigorous testing in diverse conditions and a multi-dimensional assessment of performance indicators, this research paves the way for advancements in AVLS technology that can better adapt to the dynamic nature of road environments.

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REFERENCES

Carter, R. C. 1982. Visual search with color. Journal of Experimental Psychology: Human Perception and Performance, 81, 127.

Dai, S. R., Zhu, J. K., & Li, W. 2021. Research on cockpit information prompt design based on auditory perception. Avionics Technology, 524, 9 Note: The end of this reference is incomplete, assuming it's a partial citation.

Lindner, C., Lindner, M. A., & Retelsdorf, J. 2019. Measuring self-control depletion in achievement situations: A validation of the 5-item brief state self-control capacity scale. Diagnostica, 654, 228–242.

Liu, Y. C. 2001. Comparative study of the effects of auditory, visual, and multimodality displays on drivers' performance in advanced traveler information systems. Ergonomics, 444, 425–442.

Thayer, R. E. 1990. The biopsychology of mood and arousal. Oxford University Press.

Watson, D., Clark, L. A., & Tellegen, A. 1988. Development and validation of brief measures of positive and negative affect: The PANAS scales. Journal of Personality and Social Psychology, 546, 1063.

Wu, Y. W. 2013. Research on key technologies of lane departure assistance driving under human-machine collaboration [Unpublished doctoral dissertation]. Hunan University, Changsha, China.

Zhang, X. D., Shen, W. T., & Mo, X. M. 2023. Active safety warning system for freight vehicles. Age of Automobiles, 9, 184–186.